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PHYSICS INSIGHTS FROM RECENT MAGIC AGN OBSERVATIONS

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The total set of the 14 active galactic nuclei detected by MAGIC so far includes well-studied bright blazars like Mkn 501, the giant radio galaxy M 87, but also the distant flat-spectrum radio quasar 3C 279, and an intriguing gamma-ray source in the 3C 66A/B region, whose energy spectrum is not compatible with the expectations from 3C 66A. Besides scheduled observations, so far MAGIC succeeded in discovering TeV gamma rays from three blazars following triggers from high optical states. I report selected highlights from recent MAGIC observations of extragalactic TeV gamma-ray sources, emphasizing and discussing the new physics insights the MAGIC observations were able to contribute.

Keywords: Active galactic nuclei; BL Lacertae objects; radio galaxies; gamma-rays: observations; gamma-ray telescopes

1. Introduction

Except for the radio galaxies M 87 and Centaurus A, all 27 currently known very high energy (VHE, $E \gtrsim 70$ GeV) γ -ray emitting active galactic nuclei (AGNs) are blazars,¹ assumed to have a close alignment of their highly relativistic outflows (jets) with our line of sight. Their spectral energy distributions (SEDs) are characterized by a synchrotron peak at optical to X-ray energies, and a second peak at GeV to TeV energies. The latter can be either due to inverse-Compton (IC) emission from accelerated electrons, which up-scatter synchrotron photons to high energies.² In hadronic models, instead, interactions of the jet outflow with ambient matter, proton-induced cascades, or synchrotron radiation off protons, are responsible for the high-energy photons.³ Another defining property of blazars is the high variability of their emission. For some VHE γ -ray blazars, also correlations between the X-ray and γ -ray emission were established on various time scales.⁴ For sources with a large angle between the jet and the line of sight (e.g., the radio galaxy M 87), classical IC scenarios cannot account for the VHE γ -ray emission. Models that depend less critically on beaming effects are required instead.^{5,6}

2. The MAGIC Telescope

MAGIC⁷ is currently the largest (17m- \emptyset) single-dish imaging air Cerenkov telescope. Its energy range spans from 50–60 GeV up to tens of TeV. MAGIC is sensitive to $\sim 1.6\%$ of the Crab nebula flux in 50 observing hours. Operation during moderate moonshine extends its duty cycle substantially,⁸ which is particularly important for observing variable γ -ray sources like AGNs. A second MAGIC telescope⁹ is going to be operational from April 2009 on. By stereoscopic observations, the sensitivity of MAGIC phase II is increased considerably.

3. Strong Flaring of the Radio Galaxy M 87 in February 2008

MAGIC detected a strong $9.9\text{-}\sigma$ signal from M 87 from 2008 January 30 to 2008 February 11.¹⁰ The highest flux (15% that of the Crab nebula) was recorded on 2008 February 1 at a significance of $8.0\text{ }\sigma$.

Our analysis revealed no variability in the 150–350 GeV range, while a variable (significance: 5.6σ) γ -ray flux above 350 GeV on night-to-night basis confirmed the $E > 730$ GeV variability reported earlier.¹¹ The variability restricts the VHE emission region to a size of $R \leq \Delta t c \delta = 2.6 \times 10^{15}$ cm (Doppler factor δ), and suggests the core of M 87 rather than HST-1, the brightest knot in the M 87 jet, as the origin of the γ -rays. The rapid variability alone cannot dismiss HST-1 as possible origin of the TeV photons. In early 2008, however, HST-1 was at a low X-ray flux level, whereas the luminosity of the M 87 core was at a historical maximum.¹² To further elucidate the location of the VHE emission, the H.E.S.S., VERITAS, and MAGIC collaborations performed an extensive campaign on M 87 in 2007/8.¹²

For the first time, the energy spectrum below 250 GeV could be assessed. The hardness of the spectrum, described by a power law with a spectral index $\alpha = -2.30 \pm 0.11_{\text{stat}} \pm 0.20_{\text{syst}}$ is unique among the VHE AGNs, which show either curved or softer spectra. No high-energy cut-off was found, but a marginal spectral hardening, which may be interpreted as a similarity to the VHE blazars, where such hardening has often been observed.¹³

4. Energy-Dependent Delay in the 2005 July 9 Flare of Mkn 501

During a high-flux phase of Mkn 501 in summer 2005, this blazar revealed rapid flux changes with doubling times as short as 3 minutes or less.¹⁴ For the 2005 July 9 flare, a time delay (zero-delay probability of $P = 0.026$) between the flare peaks at different γ -ray energies of $\tau_l = (0.030 \pm 0.012)\text{ s GeV}^{-1}$ towards higher energies was found.¹⁵ Such a delay can be produced by a gradual acceleration of the underlying electron population.¹⁴ Other explanations are the observation of the initial acceleration phase of a relativistic blob in the jet¹⁶ or, within an SSC scenario, a brief episode of increased particle injection.¹⁷ An energy-dependent speed of photons in vacuum,¹⁸ as predicted in some models of quantum gravity,^{19,20} can also result in a delay: When assuming a simultaneous emission of the γ -rays

(of different energies) at the source, a lower limit of $M_{\text{QG}} > 0.21 \times 10^{18}$ GeV (95% c.l.), among the best from time-of-flight measurements,^{20,21} can be established,¹⁵ which increases further if any delay towards higher energies in the source is present.

5. Blazars Detected during Optical Outbursts

Observations following high optical states of potential VHE blazars have proven very successful²² with the detection of Mkn 180, 1ES 1011+496, and recently S5 0716+71. The 18.7-h observation of 1ES 1011+496 was triggered by an optical outburst in March 2007, resulting in a $6.2\text{-}\sigma$ detection²³ at $F_{>200\text{GeV}} = (1.58 \pm 0.32) \times 10^{-11} \text{cm}^{-2}\text{s}^{-1}$. An indication for a long-term optical-VHE correlation is given, in that in spring 2007 the VHE γ -ray flux was $> 40\%$ higher than in spring 2006, when MAGIC had observed this blazar for the first time.²⁴

In April 2008, the supporting optical KVA telescope reported a bright optical state of the blazar S5 0716+71, triggering VHE observations, which resulted in a $6.8\text{-}\sigma$ detection, corresponding to a flux of $F_{>400\text{GeV}} \approx 10^{-11} \text{cm}^{-2}\text{s}^{-1}$. The source was also in a high X-ray state.²⁵

6. MAGIC J0223+430: A Gamma-Ray Source in the 3C 66A/B Region

MAGIC observed the region around 3C 66A for 54.2 h in fall 2007, resulting in the discovery²⁶ of the γ -ray source MAGIC J0223+430 at (RA, dec) = ($2^{\text{h}}23^{\text{m}}12^{\text{s}}$, $43^{\circ}0'.7$), coinciding with the catalog position of 3C 66B, a nearby ($z = 0.022$) Fanaroff-Riley type I radiogalaxy. 3C 66A, $6'.1$ away from the detected excess, can be excluded statistically as being the γ -ray source with a probability of 95.6%. When allowing for a systematic pointing uncertainty of $2'$, the exclusion probability is 85.4%. The γ -ray flux was found to be constant on the level of 2.2% the Crab nebula flux. The energy spectrum of MAGIC J0223+430 extends from 75 GeV to 3 TeV, following a power law with a photon index of $\alpha = -3.10 \pm 0.31_{\text{stat}} \pm 0.2_{\text{syst}}$. Given the likely association of MAGIC J0223+430 with 3C 66B, our detection would establish radio galaxies as a new VHE γ -ray source class. In view of the recent detection of 3C 66A as VHE γ -rays emitter,²⁷ we note that if 3C 66A was emitting γ -rays in 2007 August to December, then its flux was at a significantly lower level than in 2008. Also it cannot be excluded²⁸ that the observed spectrum is a combination of emission from 3C 66B (dominating at $E > 150$ GeV) and 3C 66A (at lower energies). Given the measured spectral index, in the improbable case that the *total* signal originates from 3C 66A, the redshift of this blazar is likely to be significantly lower than previously assumed²⁶ ($z = 0.444$ and 0.321).

7. Detection of the Distant Flat-Spectrum Radio Quasar 3C 279

VHE γ -rays were detected from 3C 279 at a $5.77\text{-}\sigma$ post-trial significance on 2006 February 23, supported by a marginal signal on the preceding night.²⁹ A zero-flux

lightcurve of the full 10-day observation can be rejected on the $5.04\text{-}\sigma$ level. This makes 3C 279 at $z = 0.536$ the most distant VHE γ -ray source. The observed VHE spectrum can be described by a power law with a differential spectral index of $\alpha = 4.1 \pm 0.7_{\text{stat}} \pm 0.2_{\text{syst}}$ between $75 - 500$ GeV. It is sensitive to the extragalactic background light³⁰ (EBL) between $0.2 - 2\text{ }\mu\text{m}$. The reconstructed intrinsic spectrum is difficult to reconcile with models predicting high EBL densities (e.g., the fast-evolution model in Ref. 31), while low-level models^{32,33} are still viable. Assuming a maximum intrinsic photon index of $\alpha^* = 1.5$, an upper EBL limit was inferred,²⁹ leaving a small allowed region for the EBL. The results support, at higher redshift, indications³³ that *Hubble Space Telescope* and *Spitzer* data correctly estimate most of the background light in the Universe.

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